Understanding Predictability of the Ocean

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LONG-TERM GOALS

The long-term scientific goals of this research project are:

1. To develop an understanding of how some observations affect ocean predictability.
2. To further develop the state-of-the-art ROMS 4D-Var by extending the observational types and applications.
3. To gain experience and develop ideas for the limitations to the predictability of oceanic processes.
4. To train a new generation of students in data assimilation and ROMS.
5. As a YIP award, to strengthen the early career and build the research path for myself as young faculty.

OBJECTIVES

The primary objectives of this project are: (i) explore the capabilities of a real-time ocean state-estimation and prediction system; (ii) to assess how particular observations may affect predictability; (iii) to compare these results with full ocean-state estimates generated from the ΨEX acoustic experiment; and, (iv) provide means to build a research program for early career scientist.

APPROACH

In this YIP award, my aim is to characterize the factors that control predictability in the ocean, particularly around Hawaii and the North Philippine Sea (which resides within the internal wave train from the Luzon Strait as well as interacting internal waves generated at the Mariana islands). To accomplish this goal requires a number of studies into understanding the role of internal tides interacting with mesoscale energy, quantifying the role of observations in understanding such difficult dynamical regimes, extending the capability of the assimilation procedure to utilize advanced observational datasets (high-frequency radar and acoustic tomography), develop further improvements to the state-estimation procedure, and to help quantify the role of errors in models. Furthermore, as a YIP award, the goal is to build a successful academic research program under

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my direction. Because of the large scope of these issues, the work carried under this YIP award both leverages and contributes to work in my other funded projects.

Despite their relatively small size, the Hawaiian island chain has a significant impact upon the atmospheric and oceanic circulations of the northern, sub-tropical Pacific. High volcanic mountains block the NE trade winds, forcing them to squeeze between the islands. Further west, these winds coalesce to form a wake that extends for 3000 km behind the Islands Xie et al. (2001). These island disturbances create significant energies at scales ranging from the sub- to meso-scale along with near-coastal processes interacting with mesoscale eddies due to the steep island topography. In addition, Hawaii is subject to large barotropic tides and combined with the steep topography, is a major source of barotropic-to-baroclinic tidal energy conversion. In the region around the islands, the internal tidal energy is as much as 50% of the dominant flow. These factors combine to create a challenging region for state-estimation and prediction (Matthews and Powell, 2011; Natarov and Powell, 2011).

As part of the NOAA-funded Integrated Ocean Observing System (IOOS) effort, I lead the ocean modeling effort of the Pacific IOOS (PacIOOS) region. The ocean model used in this research is the ONR-funded Regional Ocean Modeling System (ROMS): a free-surface, hydrostatic, primitive equation ocean model discretized with a terrain following vertical coordinate system (Shchepetkin and McWilliams, 2005). ROMS has been successfully used to model many regions of the world ocean (see `http://www.myroms.org/papers`) and is a widely used community resource.

The oceanic modeling component of PacIOOS currently employs four nested ROMS models: 4km island-chain, 1km Oahu, 100m Oahu South-Shore, and 80m Oahu West-Coast. Each grid is nested in the grid above it (both the South and West models are nested in the Oahu grid), and the 4km is nested in the real-time NCOM. This system is currently running operationally, and it assimilates the previous four days of real-time observations into the 4 and 1 km models using 4D-Var to produce nowcast state-estimates. From the nowcasts, a seven day prediction is made, which is used by the local community (e.g., Coast Guard search and rescue, Shipping Routes, etc.). These efforts are both leveraged and extended from the work in this YIP. The system currently does not employ tides, and this is a significant shortcoming, as described above.

Because each of the grids are nested, tidal solutions must be conveyed from one grid to the next. Global NCOM is run without tides, so the 4km grid imposes the barotropic tidal harmonics on its boundaries. The traditional one-way nest would simply use the fields from the 4km to impose the boundaries on the 1km nested grid; however, in this case, the grid's size makes it prohibitively expensive to store at the frequency required to properly resolve the M_2 tide in the region. The primary issue is that the baroclinic tides are not deterministic as they interact with the mesoscale and changing stratification means internal waves surface in different time and places. These two processes act to create a random phasing of the tidal expression in the surface temperature and velocity fields.

To improve forecasts of the ocean circulation, we must understand how both observations and model error (such as the incorrect tidal phasing) impact the predictability. Forecasts are limited by the growth of uncertainty, and the aim is to quantify the uncertainty in forecasting regional oceans to the observations and configuration. To understand the importance of observations, we have implemented an adjoint of the observation-space assimilation procedure for the Hawaiian regional model to quantify the sensitivity of the forecast to satellite, autonomous gliders, and long-term fixed mooring data.

As part of the Young Investigator Program, development of a dynamic research group, is one of the primary objectives. In the reporting year, in my group there were: two post-doctoral

researchers, one marine technician, and three graduate students (2 M.S. level and 1 Ph.D.). One M.S. student graduated in the spring and the second will graduate in the fall.

WORK COMPLETED

During the current reporting period, we have completed the following tasks:

i) We have had a manuscript accepted that proposes a new technique for imposing baroclinic and barotropic tides to nested model solutions from the parent interface (Janeković and Powell, 2011b). These results were detailed in the previous year report.

ii) We have a manuscript in review (Matthews and Powell, 2011) for a three-year 4D-Var assimilation experiment with the 4km Hawaiian domain using all available data, including: satellite sea surface height (alongtrack), satellite sea surface temperature (raw swath data), *in situ* ADCP, autonomous SeaGliders, Argo, *in situ* CTD measurements, drifters, and moorings.

iii) We have completed two, one-year assimilation experiments of models nested within the 4km Hawaiian domain: the 1km Oahu domain and the 80m western Oahu domain. Assimilation of data, including HF radar radial data (in last year's summary, I reported that I had modified ROMS to assimilate raw HF radials), gliders, and all data available in the Hawaiian domain, was performed within each nested grid. A manuscript is in preparation Janeković and Powell (2011a).

iv) Using the assimilation results, I have computed the contribution (or impact) of every single observation to various measures of importance in the circulation of the Hawaiian domain. These results help us to quantify which observations are crucial to the improving the predictability of the region.

v) I have a paper in review (Powell, 2011a) examining how to avoid overfitting of observations using additional outer-loops in data-space 4D-Var methods. The paper examines the proper constraint and how ignoring the constraint improves the fit to the observations, but reduces the predictive skill of the model.

vi) Most significantly, the lessons of these assimilation experiments and observational impacst **are now in operational use** with the PacIOOS ocean estimation and prediction system. Results can be found at
`http://oos.soest.hawaii.edu/pacioos/focus/modeling/ROMS_compare_variable.php`

vii) The focus of work going forward is in the North Philippine Sea. I have developed a technique for assimilating the travel times from acoustic tomographic into ROMS. This is currently being tested and a manuscript will be submitted for the special issue that is being prepared for ΨEx. This is work that is being conducted in conjunction with ONR acoustics.

viii) Mentored two post-doctoral researchers, three graduate students, and one technician.

RESULTS

Strong-constraint, 4D-Var assimilation creates increments to the flow field at the beginning of each assimilation window. Oftentimes, to match flow characteristics later in the time window, an inertial flow must be created to propagate energy or features where it is needed. We found with our exhaustive assimilation experiment that the inertial energies added can be significant. As shown in Figure 1, the tidal and internal wave frequencies were well maintained in the assimilation (notice the 12 and 24 hour periods); however, a strong enhancement of the inertial periods (greater than 30 hours) was created when assimilating without or with forcing adjustment. Without forcing adjustment, the inertial energies were enhance much more than with forcing adjustment. We are working to both characterize and minimize (where it may actually be a problem) these effects by reducing the background error and investigating a filtered increment implementation.

As discussed in the previous report, HF radar radials are superior to the artificially constructed vectors using pseudo-orthogonal radar sites. Further work with HF radials in areas of strong internal waves illustrated an issue when using the raw radials for assimilation. Internal waves reflect off of the surface of the ocean at random phase shifts and position offsets due to the varying waveguide due to inertial mesoscale energy changing the density structure. In ocean models, the bathymetry is not correct because of the discretization, and in the case of s-level models (ROMS), the bathymetry is smoothed to reduce possible pressure-gradient errors. These issues require that we remove tidal information from the observations and add the model forecasted tidal information to the observations with appropriate error. For this, we have employed spectral filtering as tidal fits are not possible due to the random phase shifts. We remove energy band below the inertial from the observations because we are interested in the inertial period that the observations are best at capturing.

Using the results of the assimilation, we are able to compute the adjoint of the entire assimilation procedure. The results of the adjoint provide quantitative information on how each observation affected the minimization of the residuals. For the more than two year, high-resolution assimilation experiment detailed in Matthews and Powell (2011), we have also generated observational impacts. Shown in Figure 2 are the results of how the transport in the Hawaiian Lee CounterCurrent are changed during the assimilation and what percentage of that change was contributed by each observation type. As shown, the gliders and HF radials provide the most information on the flow even though each instrument is more than 200km away from the transport area. By constraining the flow downstream, the HLCC transport is affected. By examining the most impactful of the individual observations, we can calculate the representer, which shows the projection of the observation onto the model dynamics revealing what the observation actually saw of the ocean. Figure 3 shows the representers from one HF radial observation over time. On the surface velocity, the radial helps to constrain the leeward circulation and in the temperature structure along a zonal transect, we see that the radial provides information that constrains the temperature near the thermocline.

We are running a fully operational system of everything described above for the PacIOOS Hawaii state estimation and forecasting system. Everyday, all data from the previous four days are assimilated into the system, and a seven day forecast is generated. The Oahu grid is then assimilated and forecast for five days, and the smaller grids do not currently assimilate operationally and forecast for three days. The impact of each observation is computed operationally, and a number of user products are generated, including: swim forecasts and particle tracking tools for search and rescue, etc.

In 4D-Var, we aim to produce an estimate from the longest time window as limited by the linearity assumption. Utilizing outer-loops, we can extend this window into the weakly nonlinear regime, which provides more constraints to the model providing a better forecast. When the outer-loops of the data-space methods are not properly constrained, it is easy to overfit the data in ways that reduce the forecast skill. I have a manuscript in review (Powell, 2011a) that shows how overfitting is similar to 3D-Var, and how to avoid it.

Mentoring of young scientists and students: Rebecca Baltes graduated with an M.S. in oceanography and is now working at the IOOS office of NOAA in Silver Springs, MD. Her degree was funded under this YIP, and her thesis was to examine the sensitivity of the forecasts around Oahu to observations performing OSSEs (Baltes, 2011). Her interest and focus was to understand the observations that most contributed to estimate the conditions of the ocean near the discharge of a pilot Ocean Thermal Exchange Converter (OTEC) power plant south of Barber's Point on the island of Oahu. OTEC is a technology that the Navy has a significant interest for generating power at Naval bases around the world. By using an Rankine engine cycle with fluorine gas cooled by deep ocean water and warmed by surface waters, turbines are used to generate electrical power that is sent back to shore. Ms. Baltes showed that the HF radars installed by Prof. Pierre Flament on the island of Oahu provide significant improvement to the forecast skill.

Colette Kerry, a Ph.D. student in my lab, has been working to characterize the internal tides in North Philippine Sea (Figure 4 and their impact on predictability as described above and in the report for ONR #N00014-10-1-0490.

Another graduate student, Abby Johnson, is working to finish her M.S. in oceanography with partial support under this grant. She has focussed on understanding the role of wind, waves, tides, circulation, and biology on plumes that emanate from the Ala Wai canal along the South Shore of Oahu. This man-made canal collects rain water from streams and other drainage sources where it discharges into the ocean due to tidal exchange and strong rain events. These plumes are often contaminated with natural bacteria (e.g., *enterococci* and *vibrio vulnificus*) that are harmful to humans. Understanding the mechanisms that most control the plume allows for us to predict beach conditions for such bacteria.

IMPACT/APPLICATIONS

We are operating one of very few operational oceanic 4D-Var estimation and ensemble prediction systems. We are also the only one that generates daily observational impact analyses that we use to monitor the observations and understand how best to improve our estimate and forecasts.

As numerical models are becoming more widely accepted in oceanographic applications, a quantified estimate of the uncertainties must accompany any forecast to aid in the understanding of the generated fields. This project will contribute to the ROMS community by deploying methods to quantify how observations contribute to prediction. The foundation for this work is present only in ROMS as it is the only model that possesses such a wide range of 4D-Var algorithms. This project will contribute to further enhancement and development of these tools and algorithms.

TRANSITIONS

The cutting edge work of the observational impact was presented at invited lectures in the past year. One was at NC State University in October, 2010, and the second was at the Gordon Research Conference on Coastal Ocean Modeling in June, 2011. The estimates of the internal wave

field in the ΨEx array will hopefully be used by the larger group in the processing and estimation of the acoustic data. The new methods for assimilating HF radar, acoustic tomography, and assessing observational impacts that are developed as part of this project will be made available to the ROMS community and will hopefully be actively used and further developed by other research groups in the U.S. and elsewhere as user competence increases.

Furthermore, the operational system generates a number of products for the public to make informed decisions about ocean conditions around Hawaii. The raw data are also available to the scientific community without conditions, and have been used for biological and other studies.

RELATED PROJECTS

This project is collaborating with the following ONR supported projects:

- "A community Terrain-Following Ocean Model (ROMS)", PI Hernan Arango, grant number N00014-08-1-0542.
- "North Pacific Acoustic Laboratory: Deep Water Acoustic Propagation in the Philippine Sea," PI Peter Worcester, ONR Grant N00014-08-1-0840.

In addition, collaborating with Kevin Heaney and Patrick Cross at Oasis, Inc., Bruce Howe and I are working with CEROS to develop an assimilation scheme that when combined with a glider dynamical model is capable of geolocating autonomous gliders while underwater.

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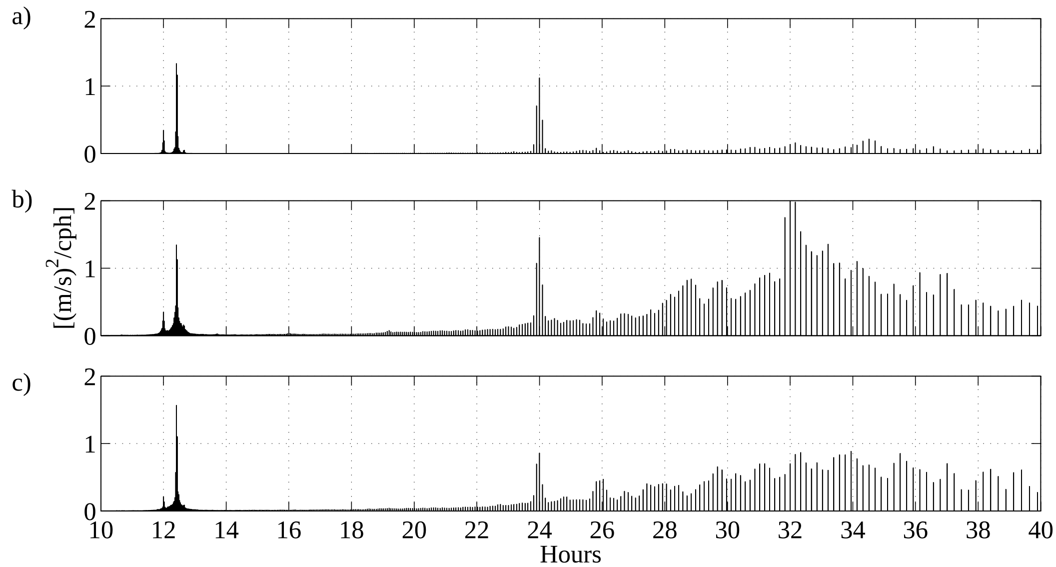

Figure 1: Power Spectral Density of energy as a function of period from three experiments: a) forward run without assimilation; b) assimilation without forcing adjustment; and, c) assimilation with forcing adjustment.

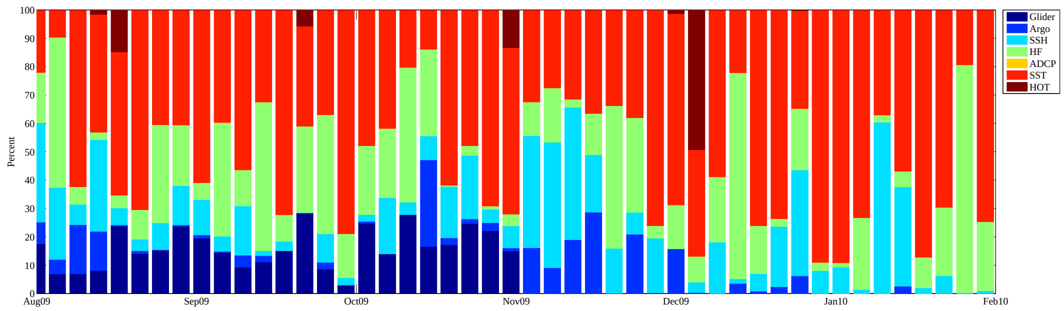

Figure 2: Impact of observations on estimation of the transport of the Hawaiian Lee Counter-Current. Although glider account for less than 1% of the observations, their contribution is significant. Likewise, the HF radar radials (although they cover only south of Oahu) have an impact on our estimation of the transport.

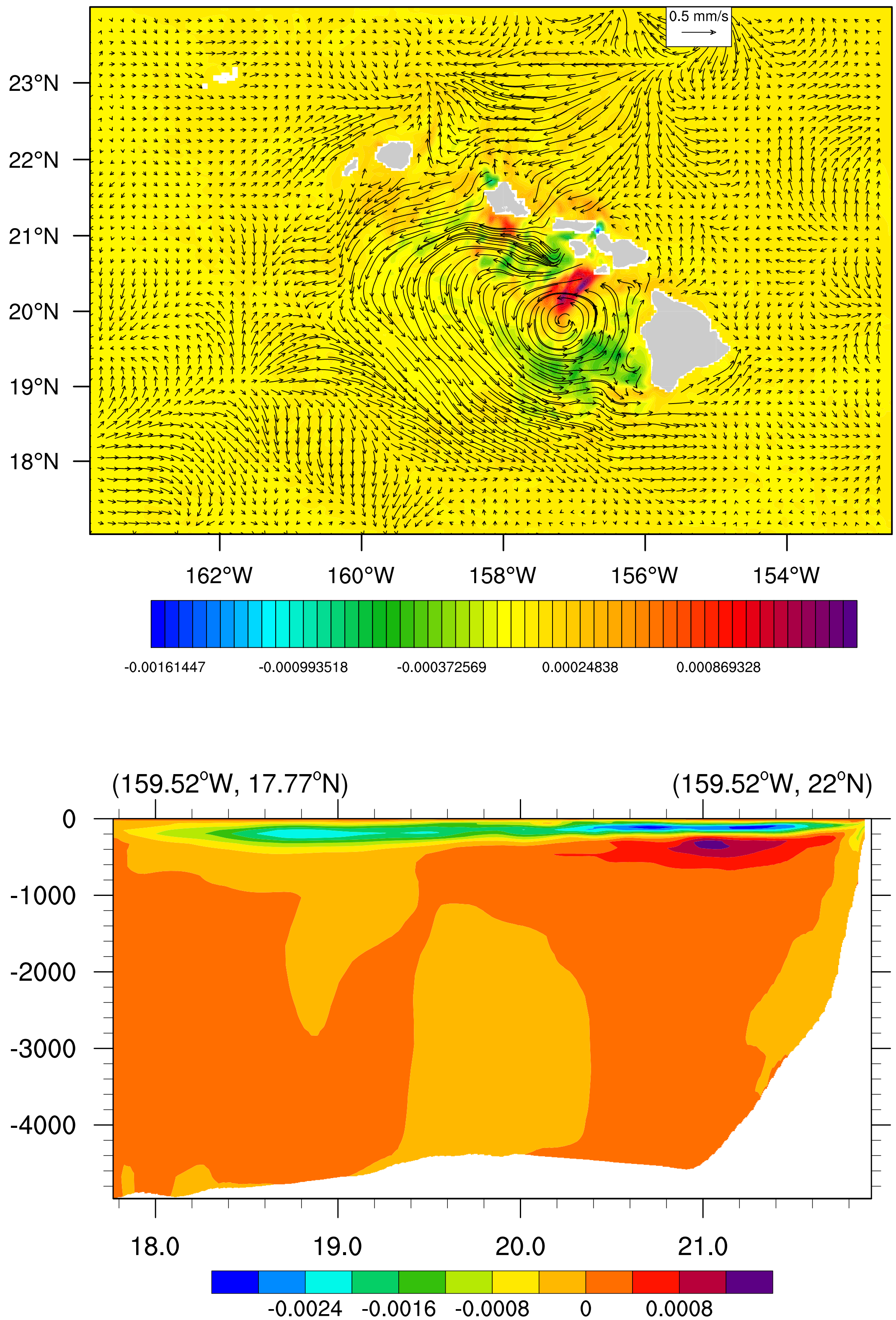

Figure 3: (top) Shows the mean projection of a single HF observation south of Oahu (covariance is shown and arrow direction is meaningless) illustrating that constraint by the HF radial is much greater than at the observation location and time. (bottom) the projection of the HF radial on the temperature field in a trasect from the island of Kauai south to the model boundary.

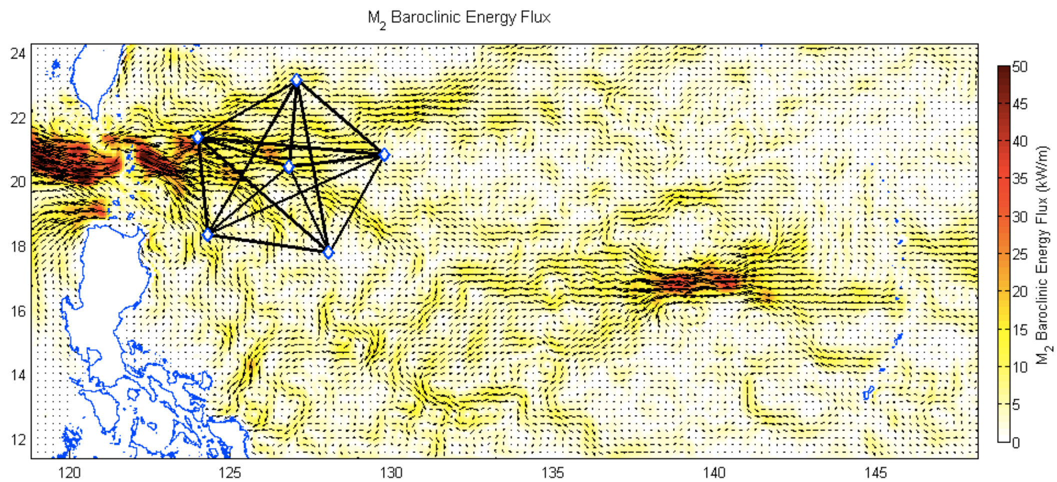

Figure 4: Baroclinic energy flux as computed for the North Philippine Sea with the ΨEx acoustic range shown. This area is a challenging and ideal laboratory for understanding predictability.